Road deposited sediment: implications for the performance of filter drains servicing strategic trunk roads

Ged Mitchell
Kehinde Oduyemi
Joseph Akunna

The definitive peer-reviewed and edited version of this article is published in Water Science & Technology and is available **at** https://doi.org/10.2166/wst.2019.319

Road Deposited Sediment: implications for the performance of filter drains servicing strategic trunk roads

Ged Mitchell, Kehinde Oduyemi and Joseph Akunna

Dr Ged Mitchell
gmitchell@bearscotland.co.uk
BEAR Scotland Limited,
BEAR House,
Inveralmond Industrial Estate,
Inveralmond Road,
Perth,
Scotland.

Dr Kehinde Oduyemi K.Oduyemi@abertay.ac.uk
Professor Joseph Akunna (corresponding author)**,**
School of Applied Sciences,
Abertay University,
Bell Street,
Dundee,
Scotland.
Email: J.Akunna@abertay.ac.uk

1.0 ABSTRACT

This study investigates the contribution of road deposited sediment (RDS) to clogging and the operational lifecycle of Highway Filter Drains (HFDs). RDS samples were collected from 9 Scottish trunk roads and fractionated into grain size classes to determine their particle size distributions (PSD). Results show that RDS PSDs, and the percentage of each grain size fraction, are highly variable. However, despite being collected from different trunk roads, PSD trends are similar, with individual RDS particles ranging in size from <63 µm to >10000 µm. Medium sand, coarse sand, fine gravel and medium gravel make up 84.1% of the total particle mass concentration, with particles >1000 µm mostly mineral or asphalt. The study also reveals that the dynamic nature of a trunk road catchment dictates that grading envelopes are essentially instantaneous values. These findings indicate that large particles from the road surface, contribute to clogging and have the potential to reduce the operational lifecycle of HFDs. The study also demonstrated that assuming a single RDS PSD profile for filter drain asset management purposes is unlikely to be representative of a trunk road catchment profile.

Key words | clogging, filter drain, particle size distribution, road-deposited-sediment,

2.0 INTRODUCTION

2.1. Background

HFDs are a widely used road drainage system and it is estimated that surface water runoff from 43% of the strategic trunk road network in Scotland is serviced by HFDs (Transport Scotland 2016). However, despite their popularity, HFDs are not a 'fit-and-forget' drainage system. This is because they are prone to clogging, a process that develops over-time and is the result of the physical accumulation of road deposited sediment (RDS) in the graded stone, which results in significantly restricted or terminated flow channels (Bruen 2006).

Clogging is exacerbated by the fact that HFDs have no pre-treatment system. As such, there is no mechanism that permits interception, removal, or storage of RDS contained in road runoff. Without any means to intercept RDS, it has the potential to overload the HFDs' graded stone, leading to clogging and premature failure, with examples shown in Figure 1. As a result, the operational lifecycle of a HFD has been estimated to be only ten years (Stylianides *et al.* 2015). It has even been suggested that HFDs prone to frequent vehicular overrun will have an operational lifecycle of around six years, because compaction of the graded stone reduces the void space and promotes a cake-layer on the surface of the HFD (Bruen *et al.* 2006).

Figure 1 | clogged HFDs due to: (a) surface cake-layer, (b) pine needles, (c) vehicle over-run, (d) litter accumulation, (e) wear-and-tear of the High Friction Surface Course, (f) vegetation intrusion.

2.2. RDS PSD grading envelopes

A review of published research evidences variability in the composition of RDS PSD grading envelopes. Ball *et al*. (1998), investigating the build-up of RDS on a suburban road, reported the median particle size values, d_{50}, ranging from 44 to 91 µm. Viklander (1998), in a study exploring RDS PSD grading envelopes, after periods of snowmelt, reported d_{50} ranging from 1000 to 4000 µm. Sansalone *et al*. (1998), measuring the physical characteristics of solids transported in lateral road runoff recorded a d_{50} ranging from 370 to 785 µm, with a mean of 555 µm. More recently, Adachi and Tainosho (2005), collecting RDS from a road and street gutter, reported d_{50} ranging from 740 to 980 µm.

Sansalone and Tribouillard (1999) and Regenmorter *et al*. (2002) in studies exploring RDS accumulation on road surfaces have identified that individual RDS particles can range in size from 1.0 µm to greater than 10000 µm. Similarly, Maglionico and Pollicino (2004), in a study exploring the build-up of RDS on urban road surfaces, demonstrated that RDS is well-sorted in terms of size, with individual particle diameters ranging from 53 to 4000 µm and d_{50} ranging from 100 to 600 µm. It has also been shown that particles exceeding 1000 µm can account for a significant percentage of the RDS mass fraction. Ellis and Revitt (1982), collecting RDS from road and street gutters, determined that particles within the range 500 to 2000 µm dominate, whilst Sartor and Boyd (1972), found that between 74.1% and 92.3% of the particles were within the range 43 and 4800 µm, the mean being 86.5%. Sansalone *et al*. (1997), investigated rainfall runoff from a motorway and found that 30% of the RDS mass was between 1000 and 10000 µm. Similarly, Sansalone and Tribouillard (1999) determined that particles with a diameter >10000 µm can exceed 7% of the RDS mass fraction.

RDS PSD grading envelopes are shaped by both natural phenomena and anthropogenic activities. Natural phenomena are primarily associated with atmospheric deposition (Murphy *et al*. 2014). Anthropogenic activities are local in nature and are associated with erosion of soil and roadside verges, vegetation detritus from surrounding land use and vehicular motion and related activities. RDS from the latter is derived from vehicle tyre and brake wear, degradation of the road surface course material, corrosion from vehicle and road infrastructure, road maintenance activities, discarded litter etc. (Loganathan *et al* 2013; Charters 2016). For example, break wear is predominantly mechanical in nature and produces particles, which vary considerably in size, ranging from ultrafine fraction to coarse fraction (Grigoratos and Martini 2015).

Numerous research studies have demonstrated that dislodgement processes (wind, rain, vehicle over-run, annual-average-daily-traffic (AADT) flow, size of contributing impervious area, level of road maintenance,) and hydraulic sorting (wind direction / strength, rain intensity, road gradient and surface roughness) influence RDS PSD grading envelopes. Vaze and Chiew (2002) highlight that due to dislodgement, only about 15% of dry samples collected from a road surface have a particle size <100 μm. Adachi and Tainosho (2005) recorded the median particle size as being between 8% and 10% and Lau and Stenstrom (2001) derived a figure of about 3%. Similarly, Sansalone and Tribouillard (1999) determined that only about 10% of the RDS mass is <50 μm and Ball *et al.* (1998) determined that the percentage of particles <200 μm ranges from 10% to 30%, with a mean of 16.8%. The aforementioned research does not however align with findings by Li *et al.* (2005) who reported that between 30% and 60% of the particle mass can be found in particles <50 μm or Gunawardana *et al.* (2014) who determined that more than 70% of the road deposited solids particles at all of the sites they tested are finer than 150 μm. It is therefore possible that differences in catchment characteristics, road dynamics and testing procedures have contributed to the discrepancies in the research noted above.

Differences in the graded stone specification of Sustainable Drainage Systems (SuDS) employing filtration and the PSD grading envelopes of stormwater particulates result in a differing balance between hydraulic profiles and filtration response. Li and Davis (2008) suggest that the critical factor determining the success of straining in filtration systems using a graded stone is the ratio between the diameter of the graded stone and that of the stormwater particulates. Knowledge of RDS PSD grading envelopes is therefore critical to the understanding of clogging and operational lifecycle of HFDs.

However, the mechanisms that govern RDS generation and PSD grading envelopes across strategic trunk road networks are lacking and poorly understood. The current lack of knowledge is a consequence of the difficulty in safely accessing strategic trunk roads for research purposes and highlights a gap in the research and performance data pertaining to this field of study. Research that has been published, tends to have been derived from geographical areas outwith the UK and, apart from a few studies, is the result of research on local roads. Moreover, RDS tends to have been collected from roads in urban areas, on one road, at one location. The research studies that are commonly referenced therefore do not have the range of AADT flows that are representative of Scottish trunk road network flows. Similarly, RDS samples have been collected from roads where international standards for the specification of the roads surface course differ from those typically used in Scotland. To complicate matters further, differences in sample collection, processing and analysis have resulted in a wide range of concentrations and distributions being reported. Taken together, these inconsistencies suggest that the RDS PSD research commonly referenced may potentially not be representative of current Scottish trunk road grading envelopes, which suggests there is a substantial research information gap.

3.0 OBJECTIVES OF STUDY

Research mapping the mechanisms that govern RDS generation and PSD grading envelopes across strategic trunk road networks are limited in number and scope. This is a consequence of the difficulty in safely accessing high-speed trunk road networks for research purposes and highlights a gap in research and performance data pertaining to this field of study.

This paper reports on a field study comparing RDS PSD grading envelopes from across the strategic Scottish trunk road network to determine the variables that govern the generation, spatial variability and PSD grading envelopes of RDS within different trunk road catchments, with the aim of establishing the impact RDS has on clogging and the operational lifecycle of HFDs.

4.0 MATERIAL AND METHODS

4.1. Site description

In this study, a total of 23 RDS samples were collected from 9 trunk roads. These being the A7, A68, A90, A912, M8, M9, M80, M90 and M876 (Figure 2).

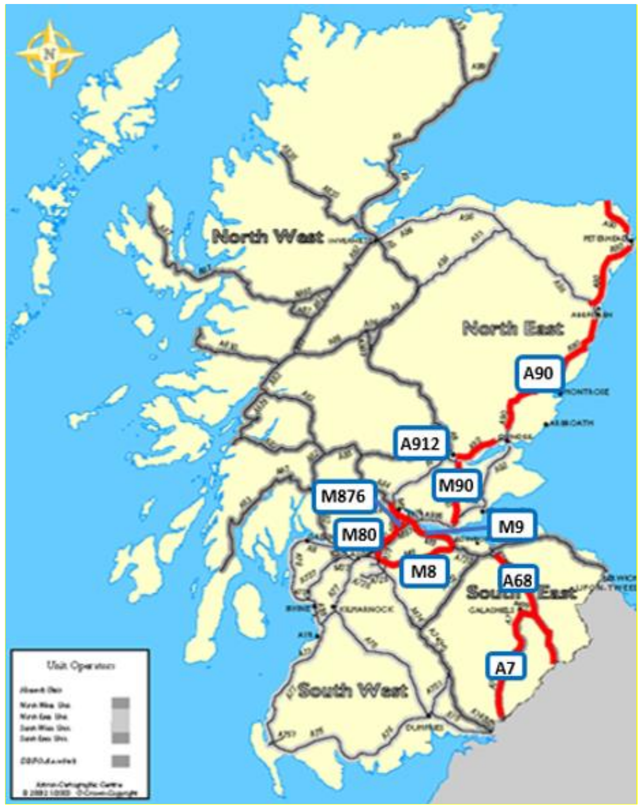


Figure 2 | Roads where RDS samples were collected.

A full spectrum of trunk road layouts, including; slip-roads, roundabouts, traffic lights, junctions and straight sections of road was included. Roads were also selected on the basis that they should be representative of typical surface course design mixtures. All roads were considered 100% impervious, had a cross-fall that diverts runoff directly to the edge of the road and had a clearly defined drainage catchment area comprising only the road surface.

Table 1 summarizes the site information for the 23 trunk road network RDS sampling sites.

Table 1 | Site information

Road								
Site ID & Road classification (A = A Road, M = Motorway)	Eastings & Northings	Land use[1]	Soil type	Speed limit (mph)	AADT	Road surface material[2]	Number of running lanes	Road surface texture depth (mm)

A7(1)	349345, 614255	U-C	alluvial	30	1686	A	1	0.5 - 0.7
A7(2)	348845, 613720	R	alluvial	60	1686	A	1	0.7 - 0.9
A7(3)	348845, 613720	R	alluvial	60	1686	A	1	0.7 - 0.9
A7(4)	349495, 614380	R	alluvial	60	1686	A	1	0.9 - 1.1
A68(1)	365087, 620115	U	brown earth	60	11843	A	1	0.7 - 0.9
A68(2)	359300, 629995	R	mineral gleys	60	3294	A	1	0.3 - 0.5
A90(1)	341640, 734298	U-C	brown earth	70	31081	A	2	>1.1
A90(2)	324355, 726130	R	mineral gleys	70	28545	A	2	0.7 - 0.9
A90(3)	328910, 729550	R	brown earth	70	26846	A	2	0.7 - 0.9
A90(4)	360750, 763100	R	brown earth	70	16725	C	2	0.3 - 0.5
A90(5)	360595, 762925	R	brown earth	70	16725	C	2	0.3 - 0.5
A912(1)	312330, 720584	R	brown earth	70	8334	A	1	0.5 - 0.7
M8(1)	300453, 668303	R	brown earth	70	28617	A	1	>1.1
M8(2)	302383, 669658	U-C-I	mineral gleys	70	55094	A	2	0.9 - 1.1
M8(3)	296588, 665678	R	brown earth	70	23243	A	2	>1.1
M9(1)	281565, 688235	R	mineral gleys	70	21796	A	2	0.7 - 0.9
M9(2)	294955, 678565	R	brown earth	70	41741	A	2	0.9 - 1.1
M9(3)	293185, 679550	R	mineral gleys	70	32314	A	2	0.7 - 0.9
M9(4)	290610, 682370	U-C-I	mineral gleys	70	32314	A	2	0.7 - 0.9
M9(5)	281594, 688211	R	mineral gleys	70	32314	A	2	>1.1
M80(1)	280229, 680261	R	brown earth	70	68194	A	2	0.7 - 0.9
M90(1)	283920, 682751	R	humus-iron podzols	70	30993	C	2	0.3 - 0.5
M876(1)	312745, 698510	R	alluvial	70	33705	A	2	>1.1

[1] U-urban, R-rural, I-industrial, C-commercial
[2] A-Asphaltic, C-Concrete

The field study relied on the availability of traffic management to facilitate safe access to the 9 trunk roads e.g. samples were taken from locations on trunk roads where road maintenance was active with traffic management. A predefined sample number could therefore not be set as there was no guarantee that traffic management would be available within the study timeframe. As a result, the decision was taken to dispense with setting a predefined sample quota and instead the aim was to collect the maximum number of samples possible, as and when traffic management permitted.

4.2. RDS sample collection

Mechanical sweeping is not a regular occurrence on any of the roads selected for this study. Therefore, the data produced only permit analysis of the spatial variability of RDS (at a single point in time) but does not allow for an assessment of temporal variability. This approach aligns with research by Sartor and Boyd (1972) and Bian and Zhu (2009), who similarly made no attempt to collect repeat samples to identify how RDS accumulates with time.

RDS was collected from the road surface using a dustpan-and-brush, similar to Li *et al.* 2015. Samples were collected three days after a rain event as it was found that the accumulated RDS is still generally moist therefore smaller particles are aggregated and this prevents them from being re-suspended during sample collection. Previous studies identify that almost all RDS accumulates within 1.0 m of the kerb-line, with around 88% within 0.3 m of the kerb (Charlesworth *et al.* 2003). Consequently, each sample was collected up to a maximum of 1.0 m perpendicular to the edge of the road, over a kerb length of 1.0 m. The mass of RDS available for collection varied from 0.5 kg to > 1.0 kg across the 23 study sites, with the variability being related to the omission of regular mechanical sweeping on any of the roads selected for this study. RDS is also heterogeneous in composition and local catchment variables and factors influencing hydraulic sorting dictated the rate, magnitude and distribution of particles dispersed across the trunk roads.

At each site, a detailed survey was undertaken to collect data pertaining to catchment characteristics and the road was assessed using a Road Surface Condition Index (RSCI) rating system. The RSCI is a delineation type method based upon inspection and observation, which is then mapped to characteristic descriptions, as shown in Table 2.

Table 2 | Road Surface Condition Index.

<table>
<tr><th>Failure Mechanism</th><th colspan="2">Service Condition</th><th colspan="2">Rating</th></tr>
<tr><td rowspan="6">Cracking

The extent / severity of cracking is determined by the percentage of road surface that is subject to transverse, longitudinal, centreline, road edge or alligator cracking.</td><td rowspan="3">Surface is reasonably new and there is very little evidence of cracking.</td><td>no defects</td><td>0</td><td>Excellent</td></tr>
<tr><td>< 5%</td><td>1</td><td>Very Good</td></tr>
<tr><td>5% to 10%</td><td>2</td><td>Good</td></tr>
<tr><td>Surface showing early signs of edge, joint, slippage, longitudinal, transverse, alligator, block etc. cracking.</td><td>10% to 15%</td><td>3</td><td>Fair</td></tr>
<tr><td>Surface showing large areas of edge, joint, slippage, longitudinal, transverse, alligator, block etc. cracking. There is also evidence of localised loss of material.</td><td>15% to 20%</td><td>4</td><td>Poor</td></tr>
<tr><td>Surface is worn out, lots of wear and tear, typically the entire segment has pockets of fatigue saturation and loss of material.</td><td>> 20%</td><td>5</td><td>Very Poor</td></tr>
<tr><th>Failure Mechanism</th><th colspan="2">Service Condition</th><th colspan="2">Rating</th></tr>
<tr><td rowspan="3">Potholes and patches</td><td rowspan="3">Surface is reasonably new and there is very little evidence of potholes and patches.</td><td>no defects</td><td>0</td><td>Excellent</td></tr>
<tr><td>< 5%</td><td>1</td><td>Very Good</td></tr>
<tr><td>5% to 10%</td><td>2</td><td>Good</td></tr>
</table>

A pothole is a hole in a road resulting from the loss of pavement material under traffic. A patch is a pothole or other surface defect that has been repaired. The rating is determined by the percentage of road surface with potholes or patches.	Evidence of pothole and patch repairs to road surface.	10% to 15%	3	Fair
	Surface showing large areas of pothole and patch repairs to road surface. There is also evidence of localised loss of material.	15% to 20%	4	Poor
	Surface is worn out. The entire segment has pockets of pothole and patch repairs to road surface and loss of material.	> 20%	5	Very Poor
Failure Mechanism	**Service Condition**		**Rating**	
Ravelling, loss of surface aggregate or polished aggregate Ravelling, bleeding, loss or polished aggregate is the progressive disintegration of a pavement surface through loss of both binder and aggregate. The rating is determined by the percentage of road surface impacted.	Surface is reasonably new and there is very little evidence of ravelling, bleeding, loss or polished aggregate.	no defects	0	Excellent
		< 5%	1	Very Good
		5% to 10%	2	Good
	Surface showing early signs of ravelling, bleeding, loss or polished aggregate.	10% to 15%	3	Fair
	Surface showing large areas of ravelling, bleeding, loss or polished aggregate.	15% to 20%	4	Poor
	Surface is worn out, lots of wear and tear, typically the entire segment has pockets of ravelling, bleeding, loss or polished aggregate.	> 20%	5	Very Poor

Source: adapted from BEAR Scotland (2010)

The RSCI rating is taken as the highest rating returned for any of the three categories in Table 1. Using the RSCI rating system, roads were rated and assigned a rating between 0 (Excellent) and 5 (Poor). In this study, roads were rated in two RSCI bandings, these being between 0 and 3 and 4 or 5. The rationale being that a road with a RSCI rating between 0 and 3 has a road surface with little evidence of fretting or fatigue on the surface. A road with a RSCI rating of 4 or 5 conversely shows signs of age, fatigue and wear and tear on the surface and there is also evidence of localised loss of material. Comparing these RSCI ratings therefore permits analysis of the impact that road condition has on the generation and PSD grading of RDS.

4.3. RDS sample processing and particle fractionation

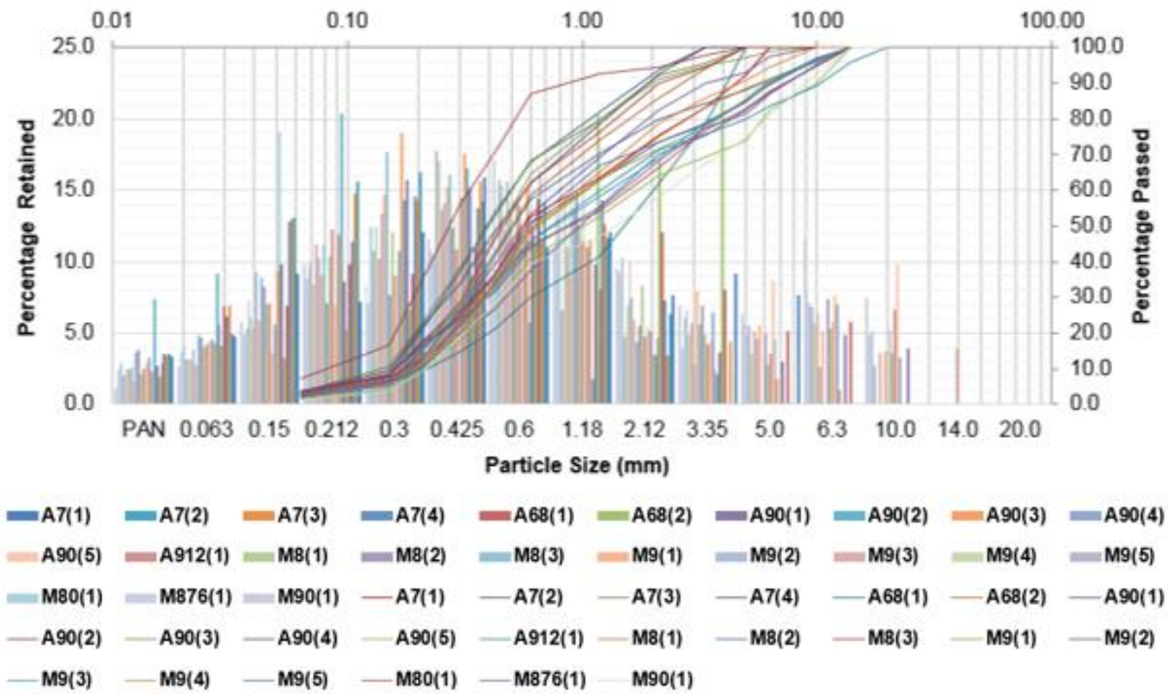
Upon arrival at the laboratory, samples were air-dried at room temperature to permit removal of materials greater than 20 mm. Samples were then oven dried at 105ºC for twenty-four hours and then dry-sieved using British Standard stainless-steel sieves. Dry sieving was selected because this methodology produces reliable PSD results and is commonly used for RDS coarse particle analysis (Sartor and Boyd 1972).

The fractionated RDS was classified according to BS 1377-2:1990 e.g. silt and clay (<63 μm), fine sand (63 - 200 μm), medium sand (200 - 600 μm), coarse sand (600 - 2000 μm), fine gravel (2000 - 6000 μm) and medium gravel (6000 - 20000 μm).

5.0 RESULTS AND DISCUSSION

5.1. RDS PSD grading envelope profiles

RDS PSD grading envelopes (% finer by mass) and corresponding mass percentage versus grain size fraction profiles for the 23 RDS samples are illustrated in Figure 3.



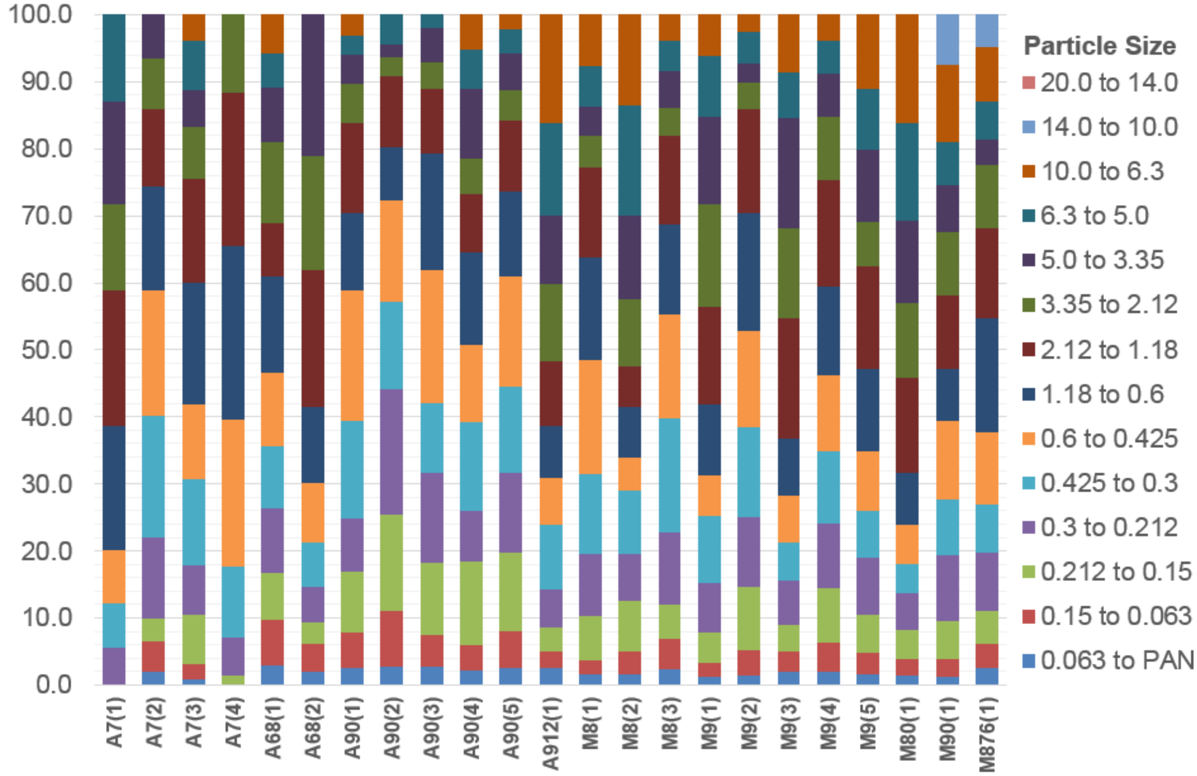


Figure 3 | RDS PSD grading envelopes and corresponding mass percentages vs grain size fraction profiles.

The findings reveal that RDS PSD gradation, and the percentage of each grain size, is highly variable across the 23 samples. However, despite being collected from 9 trunk roads, with different trunk road catchments, PSD trends are similar, with a consistent distribution of particles ranging from clay and silt to medium gravel (Table 3).

Table 3 | Distribution of Particles

	<100 µm	<200 µm	>1000 µm	>10000 µm	d_{50} (µm)
min	3.8%	9.3%	7.4%	0%	270
max	16.5%	35.7%	58.5%	10.6%	1100
mean	7.5%	15.7%	35%	2.8%	655
median	6.7%	13.7%	35.7%	3.2%	600

The results are consistent with those published by Walker and Wong (1999), with coarse sand and fine gravel particles recorded in all 23 samples and medium gravel particles recorded in 16 samples. 12 of the 23 samples also had particles with a diameter >10000 µm. The distribution of particles within the range 63 to 3350 µm is also in line with Sartor and Boyd (1972), with 5 samples exceeding 70%, 10 exceeding 80% and 8 exceeding 90%. Across the 23 samples, the d_{50} range exceeds those recorded by Sansalone *et al.* (1998) and Maglionico and Pollicino (2004), but the median d_{50} is lower than the range recorded by Adachi and Tainosho (2005).

Analysis of RSCI rating data supports this conclusion, with wide variations being noted in the results between roads with RSCI rating between 0 and 3 and a rating of 4 or 5 (Figure 4).

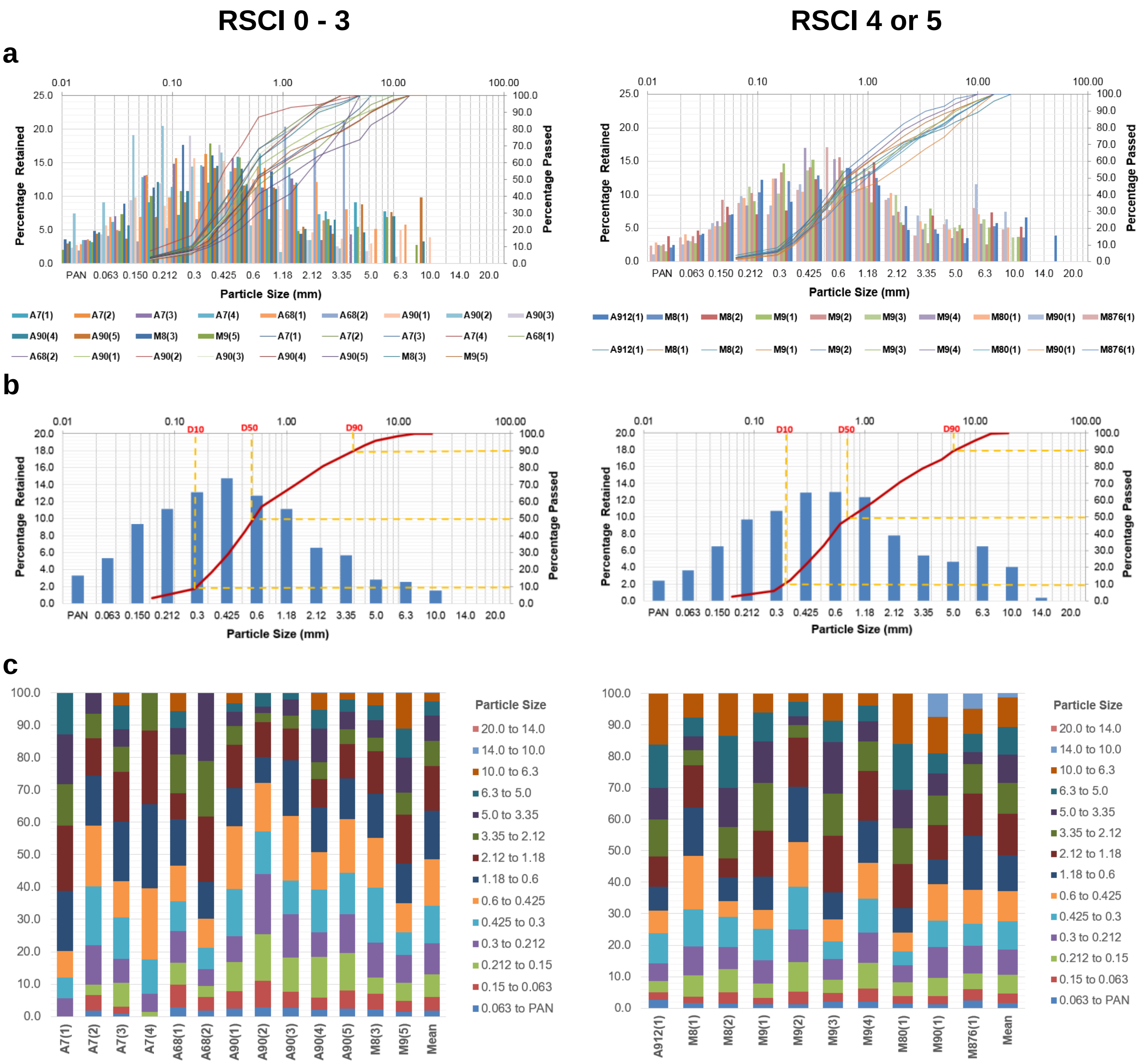


Figure 4 | (a) PSD grading envelopes (% finer by mass) for roads with a RSCI rating between 0 and 3 and 4 or 5, (b) corresponding mean RDS PSD profiles, (c) corresponding mass percentage versus grain size fraction profiles.

Roads with a RSCI rating of 4 or 5 tend to have higher speed limits, higher traffic densities and more stopping and starting of vehicles at junctions, braking zones, etc. Together these factors contribute to enhanced degradation of the road surface because they induce friction between the vehicle tyre and the road surface, which gives rise to increased rates of abrasion of the road surface and degradation of vehicle components e.g. brake linings, tyre wear etc. The results of this are reflected in the large percentage of coarse sand, fine gravel and medium gravel particles found in RDS PSD grading envelopes from roads with a RSCI rating of 4 or 5, compared to roads with a RSCI rating between 0 and 3 (Tables 4 and 5).

Table 4 | Distribution of Particles RSCI rating 0 and 3

	<100 µm	<200 µm	>1000 µm	>10000 µm	d_{50} (µm)
min	5.3%	9.3%	7.4%	0%	270
max	16.5%	35.7%	58.5%	9.8%	1100
mean	8.7%	18.1%	30.3%	1.5%	571
median	8.3%	17.3%	29.9%	0.0%	500

Table 5 | Distribution of Particles RSCI rating 4 or 5

	<100 µm	<200 µm	>1000 µm	>10000 µm	d_{50} (µm)
min	3.8%	9.5%	31.0%	0%	520
max	8.5%	16.8%	52.9%	10.6%	1100
mean	6.0%	12.5%	41.2%	4.4%	765
median	6.2%	12.1%	41.1%	4.3%	720

5.2. RDS PSD grading envelope profiles by trunk road

The greatest variability in grain-size across the 9 trunk roads was on the A90 (Table 6).

Table 6 | Distribution of Particles on the A90.

	<100 µm	<200 µm	>1000 µm	>10000 µm	d_{50} (µm)
min	6.6%	10.9%	7.4%	0%	270
max	16.5%	35.7%	47.3%	9.8%	1000
mean	9.3%	18.8%	28.4%	3.4%	556
median	7.8%	16%	29.9%	3.2%	500

On-site observation suggest that variation between the grain-size characteristics reflect differences in local catchment characteristics and road dynamics on the A90. The 5 sample locations, for example, are spread over 63 km therefore it is possible that hydraulic sorting of the RDS linked to topography, wind direction and strength, road gradient, condition of the road surface, etc. has dictated the rate, magnitude and distribution of particles dispersed across this 63 km stretch of trunk road. Different land uses and soil types are also reflected in the results. Variations in road dynamics, with 3 of the roads being asphaltic road surfaces and 2 un-reinforced concrete surface slabs, RSCI ratings vary from 1 to 3 and traffic flows range from 16,725 to 31,081 are also reflected in the results. The A90(2) is also close to an off-slip and it is possible that the induced surface tension at the braking zone has skewed the grading envelope, with a higher percentage of coarse sand, fine gravel and medium gravel particles due to the increased rate of surface course abrasion. 3 sections of the road also have a concrete central reserve safety barrier (CCRSB) and the 'barrier' effect that this safety feature creates to the movement of RDS may have skewed the actual grain-size characteristics along these sections of the A90. This relates to the fact that observations made during on-site surveys qualitatively confirmed that a CCRSB, unlike a steel safety barrier, inhibits the natural movement of RDS, litter and vegetative detritus by the normal action of wind. As a result, detritus that would normally migrate to the adjoining landscape, or would be discharged to a central reserve drainage system, forms into large masses along the base of the CCRSB (Figure 5). It is hypothesised that wind vortices dictate the shape and mass of these formations.

Figure 5 | RDS mass build-up along CCRSB.

Results from the M9 established that RDS grading envelopes had a similar range of values at all 5 sample locations, suggesting that the RDS originates from a similar source(s) (Table 7).

Table 7 | Distribution of Particles on the M9.

	<100 μm	<200 μm	>1000 μm	>10000 μm	d_{50} (μm)
min	4.4%	10.3%	31%	0%	520
max	6.4%	15.6%	41.8%	3.7%	730
mean	5.5%	12.2%	35.6%	2%	610
median	5.5%	11.8%	34.9%	2.7%	600

Similarity in the results is, in part, attributed to the fact that the 5 sample locations were located within a 20 km section of the M9 and all have similar land uses and soil types. In addition, all 5 locations had an asphaltic surface course and RSCI ratings of 4 or 5 were recorded at 4 of the sample locations. A steel central reserve safety barrier was also present at all 5 locations.

Results from the A68 established that the 2 RDS PSD grading envelopes are more heterogeneous in terms of particle size, with RDS from the A68(2) being predominantly coarser than those originating on the A68(1). The distribution of particles <100 μm being 9.8% on the A68(1) and 6% on the A68(2) and the distribution of particles <200 μm being 16.7% on the A68(1) and 9.3% on the A68(2). The distribution of particles >1000 μm also recorded a large variation, with 39.1% on the A68(1) and 58.5% on the A68(2). Neither of the roads recorded particles >10000 μm. The d_{50} ranged from 700 μm on the A68(1) to 1100 μm on the A68(2). Differences were unexpected because the sample locations are only separated by 9 km of road, both have the same land use, soil types and RSCI rating, and both are single carriageway roads with asphaltic surface courses and low traffic flows ranging from 3,294 to 11,843. Although the results at first appeared difficult to explain, the on-site survey determined that differences were attributable to the characteristics of the road, surface course material and condition of the road surface. The A68(2), for example, is on a sharp bend and therefore the road surface is under completely different load conditions to that of the A68(1). The A68(2) also has a high friction surface course (HFSC) which is near the end of its service life.

HFSC treatments are typically used to reduce traffic accidents at high-risk locations on the trunk road network and tend to correspond to locations with a high traffic density or skidding risk. In the case of the A68(2), a HFSC had been applied on the approach to a tight bend and observation identified that the braking forces being generated on the bend had left large areas with little or no HFSC, with the HFSC detritus (resin and aggregate) migrating to the kerb-line. HFSC treatments use a high polished stone value aggregate, most commonly on the Scottish trunk road network this is calcined bauxite. The grading envelope for calcined bauxite is specified in EN933-1:1997 and this stipulates that 90% of the particles must fall within the range 600 μm to 3350 μm.

The A68(2) had 57.7% of RDS particles within the range of 600 µm to 3350 µm, compared to only 45.4% on the A68(1). This supports the conclusion that the A68(2) RDS PSD grading envelope has been skewed because of the HFSC. This was confirmed by a visual inspection of the A68(2) sieved RDS particles, which highlighted that a high percentage of the particles were derived from fragmentation of the calcined bauxite HFSC.

5.3. Trunk road RDS PSD grading envelopes

The 23 samples were separated into each of the 9 constituent Scottish trunk roads included in this study and the RDS PSD profiles for these trunk roads are illustrated in Table 8.

Table 8 | Distribution of Particles across the Scottish trunk road network.

	<100 µm	<200 µm	>1000 µm	>10000 µm	d_{50} (µm)			
					min	max	mean	median
A7	9.2%	21.2%	24.2%	0.0%	400	570	448	410
A68	7.9%	13%	48.8%	0.0%	700	1100	900	900
A90	9.3%	18.8%	28.4%	3.4%	270	1000	556	500
A912	6.2%	13.7%	40.3%	10.6%	710	710	710	710
M8	7.7%	15.7%	35.3%	2.9%	460	880	653	620
M9	5.5%	12.2%	35.6%	2%	520	730	610	600
M80	7.1%	12.4%	46.1%	5.1%	900	900	900	900
M90	3.8%	9.5%	52.9%	7.5%	1100	1100	1100	1100
M876	6.1%	11%	45.2%	4.9%	980	980	980	980

5 of the 9 Scottish trunk road RDS PSDs (A7, A90, M8, M9 and M90) peaked at a particle diameter of 425 µm. Of the remaining 4 trunk roads, the A912 and M876 PSD peaked at a particle diameter of 600 µm, the M80 PSD peaked at a particle diameter of 1180 µm and the A68 PSD peaked at particle diameters of 2120 and 3350 µm.

The 23 samples were also separated into their constituent trunk roads and the data was synthesized and RDS classified according to BS 1377-2:1990 for each of the 9 Scottish trunk road network roads included in this study (Table 9).

Table 9 | RDS classified according to BS 1377-2:1990.

Trunk Road	Silt and Clay (%)	Fine Sand (%)	Medium Sand (%)	Coarse Sand (%)	Fine Gravel (%)	Medium Gravel (%)
A7	3.5	17.7	41.4	25.9	11.5	0.0
A68	2.4	10.6	25.5	20.7	31.7	2.9
A90	3.7	15.1	41.4	20.4	11.9	7.5
A912	2.5	11.2	32.0	25.4	12.5	16.4
M8	3.2	12.5	35.9	26.8	14.4	15.9

M9	2.2	10.0	37.7	25.3	17.5	7.3
M80	2.9	9.5	32.4	21.7	21.2	12.2
M90	1.2	8.4	29.8	18.8	22.8	19.1
M876	2.4	8.6	26.7	30.6	18.8	13.0
mean	2.7	11.5	33.6	24.0	18.0	10.5
median	2.5	10.6	32.4	25.3	17.5	12.2

All 9 trunk road RDS PSD grading envelopes are consistent with those published by Walker and Wong (1999). Coarse sand and fine gravel particles are recorded on all 9 trunk roads and medium gravel particles are recorded on 8 of the 9 trunk roads. The distribution of particles is also consistent with research by Regenmorter et al. (2002) and Sansalone and Tribouillard (1999) who identified that individual RDS particles accumulating on road surfaces range in size from 1.0 µm to >10000 µm. The results obtained in this study identify that medium and coarse sand particles account for the majority of RDS accumulating on road surfaces.

5.4. Implication of RDS for the operational lifecycle of HFDs

Observations made during on-site surveys qualitatively confirmed that RDS derived from agricultural farmland and/or roads that have poor or very poor service conditions can overload the filter drain graded stone and promote acceleration of a cake-layer on the surface of the filter drain (Figure 6a). It was also observed that high intensity rainfall events and the aerodynamic drag of large vehicles convey large RDS particles towards the edge of the road (Figure 6b). These two processes also fragment the RDS formations that build-up along the base of CCRSBs. When these events take place next to HFDs, the road runoff flushed into the filter drain (rich in large particles) overloads the surface of the filter drain, resulting in an exaggerated horizontal flow regime, coupled with a greatly reduced vertical component. Once the maximum capacity for the filter drain to retain RDS particles is reached, subsequently deposited particles form a cake-layer on the filter drain graded stone surface (Figure 6c). Long-term, this cake-layer impedes the management of surface water runoff from the road and can cause ponding on the road and filter drain (Figure 6d). On a high-speed trunk road network, ponding can be particularly dangerous and lead to life-threatening driving conditions because it reduces a road's surface friction, which in turn increases stopping distances and can induce aquaplaning. Moreover, spray from rainwater being thrown up by vehicle tyres can reduce visibility, which can lead to delays in reacting to events on the road. In response vehicles must slowdown, which leads to travel disruption through longer journey times.

Figure 6 | (a) deposition of eroded soil particles from surrounding farmland migrating into HFDs, (b) RDS, rich in large particles, migrating towards the edge of the road (c) completely clogged HFDs running parallel with CCRSB, (d) ponding on trunk roads and HFDs.

HFDs servicing roads generating RDS rich in large particles or high loads should therefore be accounted for when considering clogging and the operational lifecycle of HFDs. Large particles migrating from the road to the filter drain, for example, will increase the likelihood of ‘bridging’, of the void spaces within the filter drain graded stone. Bridging inhibits the downward migration of RDS particles through the filter drain graded stone matrix, which in turn increases the rate of clogging, and the formation of a cake-layer, at the surface of the filter drain. As clogging intensifies, the free void space below the clogged surface layer will become redundant.

6.0 ACCURACY OF RESULTS

Due to ‘non-point origin’ and random occurrence of RDS at any given location on the Scottish trunk road network, there are some important points to note when interpreting the grading envelopes depicted in this paper. Particles recorded in the clay and silt range for example generally represents a small fraction of the entire RDS particle fraction, the mean being 2.9% for all 23 sites. However, this may not be truly representative of a Scottish trunk road network RDS PSD grading envelope because mechanical sweeping is not a regular occurrence therefore it is likely that over an extended timeframe, the accumulating RDS has become enriched with coarser particles through re-suspension and loss of clay and silt particles. This relates to the fact that short intense rainfall events, following long dry periods, wash-off a considerable percentage of the finer fraction of the RDS load, leaving behind an RDS particle fraction containing a high percentage of large particles. It is also hypothesized that dislodgement processes associated with wind dispersion and air turbulence caused by high traffic densities, high-speed vehicle movement and a high percentage of heavy goods vehicles has likely contributed to re-suspension and loss to the surrounding environment of clay and silt particles. This is supported by Abu-Allaban *et al*. (2003) who have shown that a heavy goods vehicle contributes eight times more re-suspended RDS than a small goods vehicle. If this is the case, then the observed RDS PSD grading envelopes in this study may only partially reflect the characteristics of actual Scottish trunk road network RDS PSD grading envelopes.

Visual observation of the sieved RDS particles also qualitatively confirmed that particles >1000 µm were generally derived from deterioration of the road surface and were non-cohesive and granular in nature. Most were coated in bitumen, road paint or expansion jointing compounds and some of these particles were observed to have adhered (aggregated) to particles of a similar or larger size. As such RDS PSD grading envelopes containing particles derived from deterioration of the road surface are likely to be somewhat skewed, with envelopes with a larger percentage of particles in the coarse sand, fine gravel and medium gravel ranges. However, it is hypothesized that particle aggregation derived from deterioration of the road surface has occurred in most, if not all, of the RDS PSD research studies referenced in this paper. On that basis, one can conclude that a direct comparison can be made of the RDS PSD grading envelopes in this research and those referenced in this paper.

The results may also be skewed somewhat by the fact that several of the sampling sites had potholes containing RDS that could not be collected as the RDS was lodged firmly within the pothole and this was inaccessible with a brush-and-dustpan. However, visual observations at the time of collecting RDS samples showed that the majority of the RDS at these sites was concentrated at the side of the road and therefore the RDS PSD grading curves were likely to be typical of the site's road catchment.

7.0 CONCLUSIONS

RDS PSD grading envelopes measured as part of this study are comparable to those reported in previous studies, with a consistent distribution of particles ranging from clay and silt to medium gravel. However, the results identify that it is important to recognise that grading envelopes are essentially instantaneous values and, given the scale of a strategic trunk road network, assuming a single RDS PSD profile at any given location is unlikely to be representative of a trunk road, or trunk road catchment profile. This is based on the premise that RDS is heterogeneous in composition and local catchment variables and factors influencing hydraulic sorting will dictate the rate, magnitude and distribution of particles dispersed across strategic trunk road network.

Strategic HFDs operate under very variable catchment environments and this study has shown that assuming a single operational lifecycle profile for a filter drain servicing a trunk road or trunk road network, is unlikely to be representative across a whole trunk road or trunk road catchment.

Results from this study can also be used to develop trunk road asset management strategies to minimize the risk that roads generating RDS rich in large particles or high loads pose to the operational lifecycle of HFDs. Existing trunk road asset management inspection regimes, for example, could be modified to include an assessment of RDS build-up at known 'hot-spots' to determine whether, or not, road sweeping was required. If sweeping was required, proactive intervention to remove the RDS would ensure that the HFDs operational lifecycle could be extended.

8.0 ACKNOWLEDGEMENTS

This study was supported in part by Transport Scotland and BEAR Scotland. The writers are grateful for their continuous support.

9.0 REFERENCES

Abu-Allaban, M., Gillies, J.A., Gertler, A.W., Clayton, R., Proffitt, D. (2003). Tailpipe, resuspended road dust, and brake wear emission factors from on-road vehicles. Atmospheric Environment. 37: 5283 - 5293.

Adachi, K., Tainosho, Y. (2005). Single particle characterization of size-fractionated road sediments. Applied Geochemistry. 20: 849 - 859.

Ball, J.E., Jenks, R., Aubourg, D. (1998). An assessment of the availability of pollutant constituents on road surfaces. Science of the Total Environment. 209: 243 - 254.

Bian, Bo., Zhu, Wei. (2009). Particle size distribution and pollutants in road-deposited sediments in diVerent areas of Zhenjiang, China. Environmental, Geochemistry and Health (31): 511 - 520.

Bruen, M., Johnston, P., Quinn, M.K., Desta, M., Higgins, N., Bradley, C., Burns, S. (2006). Impact Assessment of Highway Drainage on Surface Water Quality. Centre for Water Resources Research, University College Dublin.

Charlesworth, S., Everett, M., McCarthy, R., Ordonez, A. and de Minguel, E. (2003). A comparative study of heavy metal concentration and distribution in deposited street dusts in a large and a small urban area: Birmingham and Coventry, West Midlands, UK, Journal of Environment International, Vol. 29, No. 5, pp.563 - 573.

Charters, F.J., Cochrane, T.A., O'Sullivan, A.D., (2016). Untreated runoff quality from roof and road surfaces in a low intensity rainfall climate. Science of the Total Environment 550 (2016) 265 - 272.

Ellis, J.B., Revitt D.M. (1982). Incidence of heavy metals in street surface sediments: solubility and grain size studies. Water Air Soil Pollution. 17: 87 - 100.

Gunawardana, C., Egodawatta, P., Goonetilleke A. (2014). Role of particle size and composition in metal adsorption by solids deposited on urban road surfaces. Environmental Pollution. 184: 44-53.

Grigoratos, T. & Martini, G. (2015) Break wear particle emissions: A review. Environmental Science Pollution Research 22: 2491-2504.

Lau, S. L., Stenstrom, M. K. (2001). Best management practices to reduce pollution from stormwater in highly urbanized areas. WEFTec, Chicago, Illinois, US.

Li, H., Davis, A. (2008). Urban particle capture in bioretention media. II: Theory and model development. Journal of Environmental Engineering. 419 - 432.

Li, H., Shi, A., Zhang, X. (2015). Particle size distribution and characteristics of heavy metals in road-deposited sediments from Beijing Olympic Park. Journal of Environmental Sciences, 32: 228 – 237.

Li, Y., Sim-Lin Lau., Kayhanian, M., ASCE, M., M. K. Stenstrom. (2005). Particle Size Distribution in Highway Runoff. Journal of Environmental Engineering. 131:9(1267).

Loganathan, P., Vigneswaran S., Kandasamy. J. (2013): Road-Deposited Sediment Pollutants: A Critical Review of their Characteristics, Source Apportionment, and Management, Critical Reviews in Environmental Science and Technology, 43:13, 1315-1348.

Maglionico, M., Pollicino F. (2004). Experimental analysis of the build-up of pollutants on an urban road surface. NOVATECH, 2004.

Murphy, L.U., O'Sullivan, A.D., Cochrane, T.A. (2014). Quantifying the spatial variability of airborne pollutants to stormwater runoff in different land-use catchments. Water Air Soil Pollution, 225, 1 - 13.

Regenmorter, L.C., Kayhanian, M., Chappell, R.W., Burgessor, T.E., Tsay, K. (2002). Particles and the Associated Pollutant Concentrations in Highway Runoff in Lake Tahoe, California. StormCon 2002, San Marco Island, Florida, August 12 – 15.

Sansalone, J.J., Koran, J.M., Smithson, J.A., Buchberger, S.G. (1998). Physical characteristics of urban roadway solids transported during rain events. Journal of Environmental Engineering. 124(5): 427 - 440.

Sansalone, J.J., Tribouillard, T. (1999). Variation in characteristics of abraded roadway particles as a function of particle size. Transportation Research Record No. 1690: 153 - 163.

Sartor, J.D., Boyd, G.B. (1972). Water pollution aspects of street surface contaminants. U.S. Environmental Protection Agency. EPA-R2-72-081.

Stylianides, T., Frost, M. W., Fleming, P. R., El-Jaber, A., Mageean, M., Huetson, A., Klimczak, T. (2015). Highway filter drains: precursors for maintenance management. ICE, Infrastructure Asset Management, 2 (4): 159-172.

Transport Scotland. (2016). Road Asset Management Plan for Scottish Trunk Roads. ISBN: 978-1-909948-59-4.

Vaze, J., Chiew, F.H.S. (2002). Experimental study on pollutant accumulation on an urban road surface. Urban Water, Vol. 4: 379 - 389.

Viklander, M., (1998). Snow quality in the city of Luleå, Sweden - time-variation of lead, zinc, copper and phosphorus, The Science of the Total Environment. 216: 103 - 112.

Walker, T., Wong, T.H.F. (1999). Effectiveness of Street Sweeping for Stormwater Pollution Control, Technical Report 99/8, Cooperative Research Centre for Catchment Hydrology.